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A sustainable supply chain network and optimizing on facility location and transportation network under uncertainty

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One of the key challenges in supply chain management is the design of the supply chain network, which aims to determine the optimal locations of distribution centers across different regions in order to satisfy customer demand. In the proposed model, customer demand is fulfilled through distribution centers, which receive products from manufacturing plants. This study presents an integer linear programming model that simultaneously addresses supply chain network design and facility location decisions. The objective of the model is to minimize the total costs associated with establishing distribution centers, transporting products from manufacturing plants to distribution centers, and distributing products from distribution centers to customers. To evaluate the effectiveness of the proposed model, several randomly generated test instances of different sizes were examined. Computational experiments were conducted using a linear programming solver and an iterative local search algorithm to compare their performance in obtaining optimal solutions. The results demonstrate that the iterative local search algorithm outperforms the linear programming solver by achieving optimal solutions with significantly shorter computational time across all tested instances.

Keywords*: Iterated local search algorithm, Supply chain problem, distribution centers, facility location, theory of fuzzy sets*

1. Introduction

Supply chain network design is recognized as a fundamental decision-making problem in supply chain management, as it directly influences cost efficiency, service quality, and system responsiveness. One of the core challenges in this context is determining appropriate locations for facilities so that customer demand can be satisfied effectively while operational costs are controlled. In practical supply chains, multiple echelons are involved, ranging from production units to intermediate distribution facilities and final customers, which significantly increases the complexity of network design decisions. Facility location problems constitute a major class of operations research models and play a critical role in optimizing transportation, establishment, and operational costs. Beyond identifying optimal facility locations, these problems aim to develop an efficient network structure that balances economic performance with service requirements. Applications of facility location models can be found in both public and private sectors, such as the placement of central warehouses in manufacturing systems, emergency service centers in urban planning, and logistics

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hubs in distribution networks. An appropriate configuration of facility locations has a substantial impact on overall supply chain performance, influencing cost reduction, customer satisfaction, and service reliability. Therefore, developing efficient solution approaches for facility location problems remains an important research topic. The remainder of this paper is structured as follows. Section 2 reviews related studies on facility location in supply chain networks. Section 3 presents the problem description and the mathematical formulation. Section 4 explains the solution methodology, and Section 5 discusses the computational results and conclusions.

2. Research Background

Several studies have addressed facility location problems within supply chain networks using various methodologies. Fathali et al. [6] examined minimax and minisum single-facility location problems in a bi-regional plane using linear and near-linear formulations based on block norm properties to determine optimal solutions. Memmari et al. [12] developed a facility location model emphasizing customer satisfaction, optimizing transportation time and routing via a genetic algorithm to reduce costs. Ataie et al. [2] employed a particle swarm optimization algorithm to minimize transportation costs, considering travel time and cost criteria. Poudel et al. [15] proposed a mathematical model for multimodal biofuel supply chains, integrating facility locations, biorefineries, production, storage, and routing plans to minimize overall system costs. Irawan et al. [9] tackled the multi-product facility location problem in a two-stage supply chain using integer linear programming models to reduce storage and transportation costs. Coates et al. [4] designed a facility location framework for disaster preparedness, incorporating deprivation costs and optimizing social costs alongside private costs. Ramshani et al. [16] addressed a two-level facility location problem under uncertainty, applying tabu search and heuristic algorithms to optimize the flow from production units through distribution centers to customers. Das et al. [5] focused on solid transportation facility location, proposing two heuristic algorithms—location allocation and approximate heuristics—to minimize total transportation costs. Kaya and Ozkok [10] formulated a mixed-integer nonlinear programming model to optimize a blood distribution network, including blood bank selection, hospital allocation, and inventory management. Khorramzadeh et al. [11] combined facility location with the undirected profitable rural postman problem using integer programming and branch-and-cut, showing high numerical efficiency. Aria Soleimani Koorandeh et al. [20] considered a single facility goal location problems with symmetric and asymmetric penalty functions. Soltanpour et al. [19] transformed uncertain facility location models into deterministic optimization formulations, providing efficient algorithms for optimal solutions. Alinejad [1] introduced a multi-product, multi-period closed-loop supply chain network, integrating forward and backward echelons, solved via GAMS with a case study in the Iranian dairy industry to enhance sustainability and profitability. Ghaffarifar et al. [7] proposed a multi-objective fuzzy model for vehicle location-routing, aiming to minimize costs and environmental impacts while maximizing customer satisfaction, demonstrated through a waste management case study. Moradi et al. [14] assessed the technical and scale efficiency of 15 suppliers using DEA, identifying performance gaps and suggesting improvements for supply chain efficiency. Yaser et al. [17] developed a fuzzy multi-objective model for supplier selection considering cost, service, quality, and product survival, with a case study on industrial bakery flour suppliers. Gol Mohammadi et al. [8] proposed an integrated location-routing model for a four-echelon pharmaceutical supply chain, addressing demand uncertainty via scenario-based probabilistic methods and solving small instances exactly and larger instances using a genetic algorithm. Finally, Brahami et al. [3] examined sustainable supply chain networks, optimizing facility location and transportation network design using a multi-objective model solved with a genetic algorithm and mixed coding.

3. Problem Statement

This study considers a two-echelon supply chain consisting of factories, distribution centers, and customers. At the first level, products are shipped from factories to distribution centers, while at the second level, distribution centers are responsible for delivering products to customers, as illustrated in Figure1.

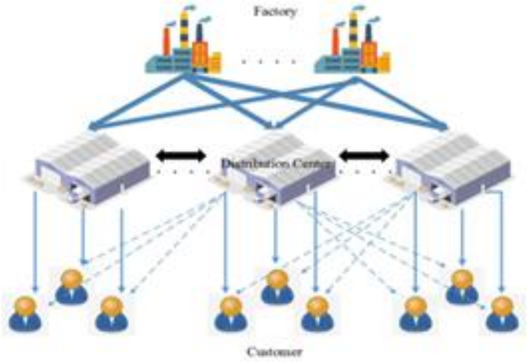

Figure 1: Two-level distribution system in the supply chain problem

The main decision problem is to determine the number and locations of distribution centers to be established, each of which incurs a fixed establishment cost and has a limited handling capacity. The objective is to configure the supply chain network in a way that minimizes the total system cost, including the costs associated with establishing distribution centers, transporting products from factories to distribution centers, and distributing products from distribution centers to customers. At the same time, the network should ensure an acceptable level of service quality. Distribution centers may exchange products with one another in case of disruptions or capacity shortages, while direct interactions between customers are not allowed. To reduce delivery delays, multiple vehicles are considered, and the transportation time must not exceed a predefined maximum limit. Furthermore, distribution centers can receive products from any factory, providing flexibility in product flows across the network.

3.1. Mathematical model of the problem

Mathematical Model Description [18] is presented below:

Sets:

F: Set of production facilities (factories).

P: Set of candidate locations for establishing distribution centers.

C: Set of customer nodes.

D: Set of distribution center types.

L: Set of available vehicles used for product transportation, either for delivery or transfer.

Parameters:

ω_{dp}: Fixed establishment cost of a distribution center of type d at location p

ω_{fpl}: Transportation cost incurred when shipping products from factory f to distribution center p using vehicle l.

ω_{pcl}: Cost associated with delivering products from distribution center p to customer c via vehicle l.

ω_{pql}: Cost of transferring products between distribution centers p and q using vehicle l.

β_d: Cost parameter related to distribution center type d.

δ_l: Unit transportation cost associated with vehicle l.

T_{fp}: Maximum allowable transportation time from factory f to distribution center p.

T_{pc}: Maximum allowable transportation time from distribution center p to customer c.

T_{pq}: Maximum allowable transportation time between distribution centers p and q.

α_d: Handling capacity of a distribution center of type d.

D_c: Demand level of customer c.

Decision variables:

X_{fpl}: A binary variable that takes the value 1 if products are transported from factory f to distribution center p using vehicle l, and 0 otherwise.

Y_{pcl} : A binary variable equal to 1 when products are delivered from distribution center p to customer c by vehicle l; otherwise, it is 0.

Z_{dp} : A binary variable indicating whether a distribution center of type d is established at location p.

V_{pql} : A binary variable that equals 1 if product transfer occurs between distribution centers p and q using vehicle l, and 0 otherwise.

$$\omega_{dp} = \sum_{d\epsilon D} \beta_d \sum_{p\epsilon P} Z_{dp} \tag{1}$$

$$\omega_{fpl} = \sum_{l\epsilon L} \delta_l \sum_{f\epsilon F} \sum_{p\epsilon P} dist(f.p)\, X_{fpl} \tag{2}$$

$$\omega_{pcl} = \sum_{l\epsilon L} \delta_l \sum_{p\epsilon P} \sum_{c\epsilon C} dist(p.c)\, Y_{pcl} \tag{3}$$

$$\omega_{pql} = \sum_{l\epsilon L} \delta_l \sum_{p\epsilon P} \sum_{p\epsilon P} \underset{q<p}{dist(p.q)\, V_{pql}} \tag{4}$$

$$min\left(\omega_{dp} + \omega_{fpl} + \omega_{pcl} + \omega_{pql}\right) \tag{5}$$

Subject to

$$\sum_{d\epsilon D} Z_{dp} \leq 1. \ \ \forall p\epsilon P \tag{6}$$

$$\sum_{l\epsilon L} \sum_{p\epsilon P} Y_{pcl} = 1. \ \ \forall c\epsilon C \tag{7}$$

$$\sum_{l\epsilon L} \sum_{f\epsilon F} X_{fpl} = \sum_{f\epsilon F} l \times \sum_{d\epsilon D} Z_{dp}. \ \ \forall p\epsilon P \tag{8}$$

$$\sum_{l\epsilon L} \sum_{c\epsilon C} D_c Y_{pcl} \leq \sum_{d\epsilon D} \alpha_d Z_{dp}. \ \ \forall p\epsilon P \tag{9}$$

$$T_f^{loading} + T_{fp}^{transition} + T_p^{unloading} \leq T_{fp}. \ \ \forall f\epsilon F. \forall p\epsilon P \tag{10}$$

$$T_p^{loading} + T_{pc}^{transition} + T_c^{unloading} \leq T_{pc}. \ \ \forall p\epsilon P. \forall c\epsilon C \tag{11}$$

$$T_p^{loading} + T_{pq}^{transition} + T_q^{unloading} \leq T_{pq}. \ \ \forall p\epsilon P. \forall q\epsilon P \tag{12}$$

$$\sum_{d\epsilon D} Z_{dp} + \sum_{d\epsilon D} Z_{dq} \leq \sum_{l\epsilon L} V_{pql} + 1. \ \ \forall p\epsilon P. \forall q\epsilon P. q < p \tag{13}$$

$$Z_{dp} \epsilon \{0.1\}. \ \ \forall d\epsilon D. \forall p\epsilon P \tag{14}$$

$$X_{fpl} \epsilon \{0.1\}. \ \ \forall f\epsilon F. \forall p\epsilon P. \forall l\epsilon L \tag{15}$$

$$Y_{pcl} \epsilon \{0.1\}. \ \ \forall p\epsilon P. \forall c\epsilon C. \forall l\epsilon L \tag{16}$$

$$V_{pql} \epsilon \{0.1\}. \ \ \forall p\epsilon P. \forall q\epsilon P. \forall l\epsilon L \tag{17}$$

In the proposed mathematical formulation, Equation (5) defines the objective function of the model. The objective is to minimize the total cost of the supply chain network, which consists of several components: the fixed cost of establishing distribution centers (ω_{dp}), the transportation cost from factories to distribution centers (ω_{fpl}), the delivery cost from distribution centers to customers (ω_{pcl}), and the inter-distribution transportation cost. The latter component is computed based on Equations (1) – (4), which capture the cost structure of product transfers between distribution centers.

Supply Chain Network Assumptions

*The supply chain structure is modeled as a two-echelon system comprising factories, distribution centers, and customers.

* Customer demand is fully satisfied by the distribution centers.

* Each distribution center has a predetermined and limited capacity.

*Distribution centers can be established at any predefined candidate location.

* Customer locations are known in advance, whereas the locations of distribution centers are decision variables.

4. Model Implementation

This section presents the implementation of the proposed algorithm for solving the two-level supply chain problem. To achieve faster computational performance compared to the iterative local search algorithm, a set of heuristic algorithms [13] was employed. The iterative local search algorithm begins with an initial solution and iteratively explores neighboring solutions, selecting the best candidate as the current solution until a predefined number of iterations is reached. The construction of the initial solution consists of three stages. In the first stage, a subset of candidate locations for distribution centers is randomly chosen. In the second stage, customers are assigned to the nearest selected locations while respecting the constraints defined in the mathematical model. In the final stage, any distribution center without assigned customers is removed from the selected set, ensuring that only relevant facilities remain active.

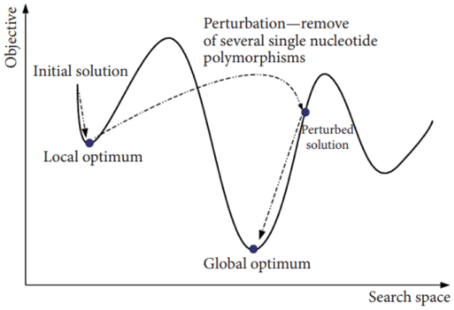

Figure 2: Iterative local search process

In this section, computational experiments are conducted to assess the performance of the iterative local search method. Test instances of varying sizes—small, medium, and large—were generated randomly to evaluate the effectiveness of the proposed approach. The experiments were performed using two distinct methods. The first method employs a linear programming solver to address linear programming problems and serves as an exact algorithm. The second method utilizes an iterative local search heuristic, classified as an approximate algorithm, which was implemented within the MATLAB software environment. The problem-solving parameters applied in these experiments are summarized in the table below.

Table 1: Problem parameters

Amount			
Type 1	Type 2	Type 3	
1000	2500	4000	Cost of establishing each distribution center
150	250	350	Cost of establishing each distribution center
20	20	20	Number of product requests by each customer
80	80	80	Number of products produced by each factory
15	20	25	Cost of transporting the product by vehicle

Each test instance was executed and evaluated ten times to ensure consistency. For small and medium-sized instances, both the linear programming solver and the iterative local search algorithm produced identical solutions. However, the iterative local search method required slightly longer execution time due to the number of moves needed to explore neighboring solutions. Increasing the number of moves enhances the algorithm's ability to approach the optimal solution but also extends computation time. For larger instances, the iterative local search algorithm outperforms the linear programming solver, providing superior solutions while maintaining competitive execution times. Experiments were conducted to evaluate the model under varying conditions, including modifications in distribution center establishment costs, storage capacities, and transportation costs, as summarized in Table 1.

Table 2: New parameter values

Amount			
Type 1	Type 2	Type 3	
1200	2500	6500	Cost of establishing each distribution center
50	100	150	Cost of establishing each distribution center
20	20	20	Number of product requests by each customer
80	80	80	Number of products produced by each factory
10	10	10	Cost of transporting the product by vehicle

Experiment 1:

The cost of establishing distribution centers (β_d) was incrementally increased to examine its impact on the minimum implementation cost. Table 4 presents the results, showing that as the establishment cost rises by 100 units in each iteration, the corresponding minimum implementation cost also increases, as illustrated in the accompanying graph.

Table 3: Results from changing the parameter β_d and running the linear programming solver on the samples

Cost	β_{d_3}	β_{d_2}	β_{d_1}	
135644/985	(6499 6500 6501)	(2499 2500 2501)	(1199 1200 1201)	1
135844/965	(6599 6600 6601)	(2599 2600 2601)	(1299 1300 1301)	*2*
136044/985	(6699 6700 6701)	(2699 2700 2701)	(1399 1400 1401)	3
136244/980	(6799 6800 6801)	(2799 2800 2801)	(1499 1500 1501)	4
136444/965	(6899 6900 6901)	(2899 2900 2901)	(1599 1600 1601)	5

Similarly, adjustments to distribution center storage capacities and vehicle transportation costs were analyzed. Increasing the storage capacity of distribution centers generally reduces the minimum implementation cost up to a certain threshold, beyond which additional capacity does not affect the cost. In contrast, raising vehicle transportation costs results in a proportional increase in the minimum implementation cost. These results demonstrate the sensitivity of the supply chain model to key parameters and provide insights into optimizing facility location, capacity planning, and transportation decisions.

5. Results

This study focused on the design of a supply chain network aimed at optimizing product distribution to customers while minimizing overall costs. The iterative local search algorithm was employed to determine the optimal number and placement of distribution centers. Experimental results demonstrate that the iterative local search method outperforms the linear programming solver, particularly for large-scale instances. These findings suggest that for large-scale facility location problems within supply chain networks, the iterative local search algorithm is a more effective solution approach. Furthermore, sensitivity analysis under varying problem parameters and uncertain conditions revealed that changes in these parameters can either increase or decrease the minimum implementation cost. For future research, the model can be extended by incorporating additional components such as suppliers and warehouses, as well as by considering gray system states and other complex scenarios to further enhance the robustness and applicability of the supply chain design model.

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